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PERSONAL COMMUNICATIONS SERVICES:
IMPROVING THEATER DEPLOYABLE COMMUNICATIONS
FOR THE 21ST CENTURY

by

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June, 1994

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Personal Communications Services (PCS) may be the key ingredient for vastly improved military communications capabilities at the turn of the century. The Federal Communications Commission (FCC) defines PCS as "a family of mobile or portable radio communications services which could provide services to individuals and businesses and be integrated with a variety of competing networks...the primary focus of PCS will be to meet communications requirements of people on the move." Today's generation of Theater Deployable Communications, which provides joint tactical communications to deployed forces, is the Tri-Service Tactical Communications (TRI-TAC) system. A description of TRI-TAC's family of equipment, network topology, typical employment, and critical limitations is presented in this thesis. Five commercial Mobile Satellite Services (MSS) are described as viable candidates for augmenting existing communications systems. Cellular design principles such as frequency reuse, cell splitting, channel access methods, and propagation factors are also addressed. Finally, a framework for comparison of the candidate MSS systems is proposed as a baseline for further studies into the most beneficial implementation of PCS into theater deployable communications systems for the future.

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Personal Communications Services:
Improving Theater Deployable Communications
for the 21st Century

by

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ABSTRACT

Personal Communications Services (PCS) may be the key ingredient for vastly improved military communications capabilities at the turn of the century. The Federal Communications Commission (FCC) defines PCS as "a family of mobile or portable radio communications services which could provide services to individuals and businesses and be integrated with a variety of competing networks...the primary focus of PCS will be to meet communications requirements of people on the move." Today's generation of Theater Deployable Communications (TDC), which provides joint tactical communications to deployed forces, is the Tri-Service Tactical Communications (TRI-TAC) system. A description of TRI-TAC's family of equipment, network topology, typical employment, and critical limitations is presented in this thesis. Five commercial Mobile Satellite Services (MSS) are described as viable candidates for augmenting existing communications systems. Cellular design principles such as frequency reuse, cell splitting, channel access methods, and propagation factors are also addressed. Finally, a framework for comparison of the candidate MSS systems is proposed as a baseline for further studies into the most beneficial implementation of PCS into theater deployable communications systems for the future.

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I. INTRODUCTION

Within the past few years, there has much discussion on topics such as C4I for the Warrior, Global Command and Control System, Information Warfare, and a New World Order. As a result, mobile communication requirements are on the rise, and personal communications services (PCS) have emerged as the focus of much attention.

PCS is a general term which encompasses a variety of mobile communications services. It has materialized from numerous technologies dealing with digital modulation schemes, cellular and wireless telephones, low earth orbiting satellite applications, and evolving network protocols. PCS has been described by various communications journals in the following ways:

1. PCS is a service not a particular technology. PCS draws on the technologies of digital modulation, cellular and cordless telephones, and sophisticated network protocols. Most PCS proposals envision a portable lightweight instrument providing users with access to a ubiquitous public network. [Ref. 1: p. 52]

2. PCS is a generic term referring to mobile communication services in which the user possesses a personal handset or cordless telephone that can be used in a number of pedestrian, office, residential and vehicular settings. [Ref. 2]

3. PCS encompasses a broad range of radio communications services that free individuals from the constraints of the wireline public switched telephone network and enable them to communicate when they are away from their home or office telephone. [Ref. 3]

4. With PCS, we can communicate from person to person, regardless of where we are physically located. While PCS as a class of services embraces a wide range of capabilities, from simple paging and telephony to more advanced functionality, the basic benefit is the ability to communicate from virtually anywhere to virtually anywhere else. [Ref. 4: p. 30]

The Federal Communications Commission (FCC) defines PCS as "a family of mobile or portable radio communications services which could provide services to individuals and businesses and be integrated with a variety of competing networks...the primary focus of PCS will be to meet communications requirements of people on the move." [Ref. 5: p. 22]

Personal Communications Services may be the key ingredient for vastly improved military communications capabilities at the turn of the century. Today's generation of Theater Deployable Communications (TDC), which provides joint tactical communications to deployed forces, is the Tri-Service Tactical Communications (TRI-TAC) system. A description of TRI-TAC's family of equipment, network

topology, typical employment, and critical limitations will be presented in the upcoming chapters. Then, in order to provide a better understanding of the technical issues concerning PCS, cellular design principles such as frequency reuse, cell splitting, channel access methods, spread-spectrum techniques, and radio frequency propagation factors will also be addressed. Once a technical foundation has been established, five commercial Mobile Satellite Services (MSS) will be presented as viable candidates for augmenting existing communications systems. A brief description of each MSS system will be given with particular attention to important technical characteristics and subscriber services. Finally, a proposed framework for comparison of the candidate MSS systems will serve as a baseline for further studies into the most beneficial implementation of PCS into the current system. In the end, this thesis will identify several deficiencies in the current TDC system, propose several MSS augmentations, and provide a framework for demonstrating the technical feasibility, additional capabilities, and benefits of incorporating PCS into theater deployable communications systems for the future.

II. TRI-TAC

A. OVERVIEW

The existing joint communications program, Tri-Service Tactical Communications (TRI-TAC), provides the primary Theater Deployable Communications (TDC) for Joint Task Force (JTF) combat operations. TRI-TAC was conceived in 1971 to foster communications interoperability among the services through a standardized suite of tactical switched communications equipment. TRI-TAC is the Air Force's current "common-user" tactical communications system used to interconnect deployed bases, installations, and headquarters elements with each other and rear echelon support organizations. Essentially, a TRI-TAC deployment provides the same core services and capabilities available on a typical fixed Air Force base. In short, TRI-TAC is a complete TDC package which is totally interoperable within itself and with existing service systems, including the Defense Communications System (DCS) and NATO systems. This chapter will introduce the TRI-TAC family of equipment and the network topologies typically employed during JTF operations.

B. TRI-TAC FAMILY OF EQUIPMENT

Functionally, TRI-TAC consists of voice, record and data terminals, automatic circuit and message switches, automated technical control facilities, multiplexing equipment, and transmission assemblages [Ref. 28: p. 87]. Additionally, a

standardized communications security (COMSEC) suite provides the TRI-TAC system with end-to-end security throughout its tactical communications network. While a detailed discussion on COMSEC is beyond the scope of this paper, the major equipment associated with TRI-TAC's primary services will be addressed below.

The TRI-TAC system provides the end-user with voice, record (message) and data communications via automatic circuit and message switches. The heart of a TRI-TAC communications network is made up of the TTC-39A Circuit Switch (CS) and TYC-39 Message Switch (MS).

1. TTC-39A Circuit Switch

The TTC-39A CS is a tactical four-wire, modular, automatic telephone central office [Ref. 24: p. B-1]. It supports 744 total external lines (96 analog, 648 digital) at the standard TRI-TAC circuit and trunk group channel rates of 16/32 kbps, and also provides limited interfaces to commercial analog central office and PBX equipment. The TTC-39A can also trunk to other TTC-39As, the TYC-39 MS, unit level transportable switchboards, such as the SB-3865, and DSN switches for connectivity into the DCS. The two TRI-TAC telephones routinely used with a TTC-39A switch are the KY-68 Digital Secure Voice Terminal and TA-954 Digital Nonsecure Voice Terminal. These ruggedized terminals interface with the switch at standard TRI-TAC loop rates of 16/32 kbps, using Continuously Variable Slope Delta (CVSD) modulation. A

variety of two-wire and four-wire analog instruments are supported by the TTC-39A version, including the TA-838 and STU-III. Finally, the TTC-39A CS provides limited nodal control, as well as extensive circuit and trunk testing capabilities.

2. TYC-39 Message Switch

The TYC-39 MS is a 50-line store-and-forward message switch [Ref. 24: p. B-1]. An appropriately accredited TYC-39 can handle both General Service (GENSER) or "R" traffic, which includes classification levels up to and including Top Secret and SIOP, and Defense Special Security Communications System (DSSCS) or "Y" traffic, which includes SCI and other sensitive information requiring special handling. The TYC-39 supports interfaces with other message switches, such as AUTODIN, via interswitch trunks (ISTs), and standard Mode I and II terminal interfaces. The TYC-39 can trunk at the TRI-TAC channel rate of 16 kbps, with a 50-line capacity, providing increased message throughput in a tactical battlefield environment. Like the TTC-39, the TYC-39 has integrated test equipment for troubleshooting ISTs and message circuits.

3. TSQ-111 Communications Nodal Control Element

For technical control, the TSQ-111 Communications Nodal Control Element (CNCE) is the "nerve center" of a TRI-TAC communications installation. This S-280 shelter-mounted component manages communications resources, monitors equipment and circuit quality, and detects and isolates faulty or degraded circuits. It accomplishes these functions through a

suite of fully programmable automated test equipment, and a computer-controlled circuit rerouting capability. The CNCE serves as the central interface between the circuit/message switches and transmission assemblages. External interfaces to the TSQ-111 equipment shelter are accomplished using standard 26-pair copper cable or coaxial cable. The TSQ-111 has both an analog and digital capability [Ref. 24: p. B-3].

4. Transmission Assemblages

TRI-TAC transmission assemblages can be divided into two main types: Digital Group Multiplex (DGM) and Ground Mobile Forces (GMF).

a. *Digital Group Multiplex Equipment*

The DGM equipment includes the TRC-170 digital tropospheric scatter radios, TSQ-146 Multiplexer Van, and RT-1462 TSSR (Tropo-Satellite Support Radio). Large transmission and switching assemblages, such as the TRC-170 or TTC-39A, are housed in standard portable equipment shelters (S-250, S-280, or S-530) and have a combined weight of approximately 8,500 lbs [Ref. 26: p. 18-9]. When being transported by M-720 or M-880 mobilizers, the physical dimensions of these components are approximately 8′ x 20′; plus, a pair of 9.5 or 6.0 foot diameter antennas must be transported separately. The TRC-170 radio system is a 32-channel, maximum 2048 kbps, tropospheric scatter radio that provides reliable, bulk-encrypted communications links between bases separated by up to 150 miles [Ref. 26: p. 18-2]. For shorter links, not to exceed 10

miles, the RT-1462 TSSR can be used for line-of-site (LOS) microwave radio communications between a remote tropo/satellite site and the main communications facility. The TRC-170 can also be configured in a LOS mode for shorter distances if necessary. Various factors including atmospherics and terrain impact the actual attainable range in any given situation. The TRC-170 family of transmission equipment performs the primary wideband communications trunking between major nodes of a deployed JTF.

b. Ground Mobile Forces Equipment

GMF equipment includes the TSC-94A and TSC-100A tactical multi-channel satellite terminals which provide the primary theater satellite communications capability. The TSC-94A (8-foot diameter antenna) is a point-to-point SHF terminal which can support a maximum of 24 individual channels. The TSC-100A (8/20-foot diameter antenna) can support up to 72 individual channels or be configured in a nodal "hub-spoke" network configuration with up to four other terminals [Ref. 24: pp. B6-B7]. Despite the different nomenclature, DGM and GMF equipment are completely interoperable, along with the entire TRI-TAC family, through a standard multiplex architecture based on a 16/32 kbps CVSD channel rate.

The previously described equipment (switches, technical control, and transmission media) form the core of the TRI-TAC family of equipment.

C. NETWORK TOPOLOGY

The *TRI-TAC communications system* typically supports Air Force bare base operations; Desert Shield/Desert Storm (DS/DS) is a good example of what the Air Force terms "bare base operations." The system supports Command and Control (C^2) at all levels by providing reliable and flexible communications capabilities. Specialized C^2 data, intelligence products, weather forecast data, and general purpose information all pass through a deployed TRI-TAC system. TRI-TAC systems not only connect bases, installations, and headquarters elements within a theater of operations, they also extend connectivity back to the CONUS and into other theaters by way of DCS gateways. The remainder of this section demonstrates how TRI-TAC components are used to support a typical Air Force deployment within a Joint Task Force (JTF) framework.

1. Air Force Component Headquarters

Figure 1, on the next page, illustrates how key TRI-TAC components support an Air Force Component Headquarters (AFCH) when deployed as part of a JTF [Ref. 44].

The AFCH is tied to the JTF HQ via tropospheric scatter radio (TRC-170) and/or SHF satellite (TSC-100A); the distance between the two headquarters generally determines the transmission medium used. If possible, both media are used for redundancy and added capacity. Links to the other service components are established in basically the same manner.

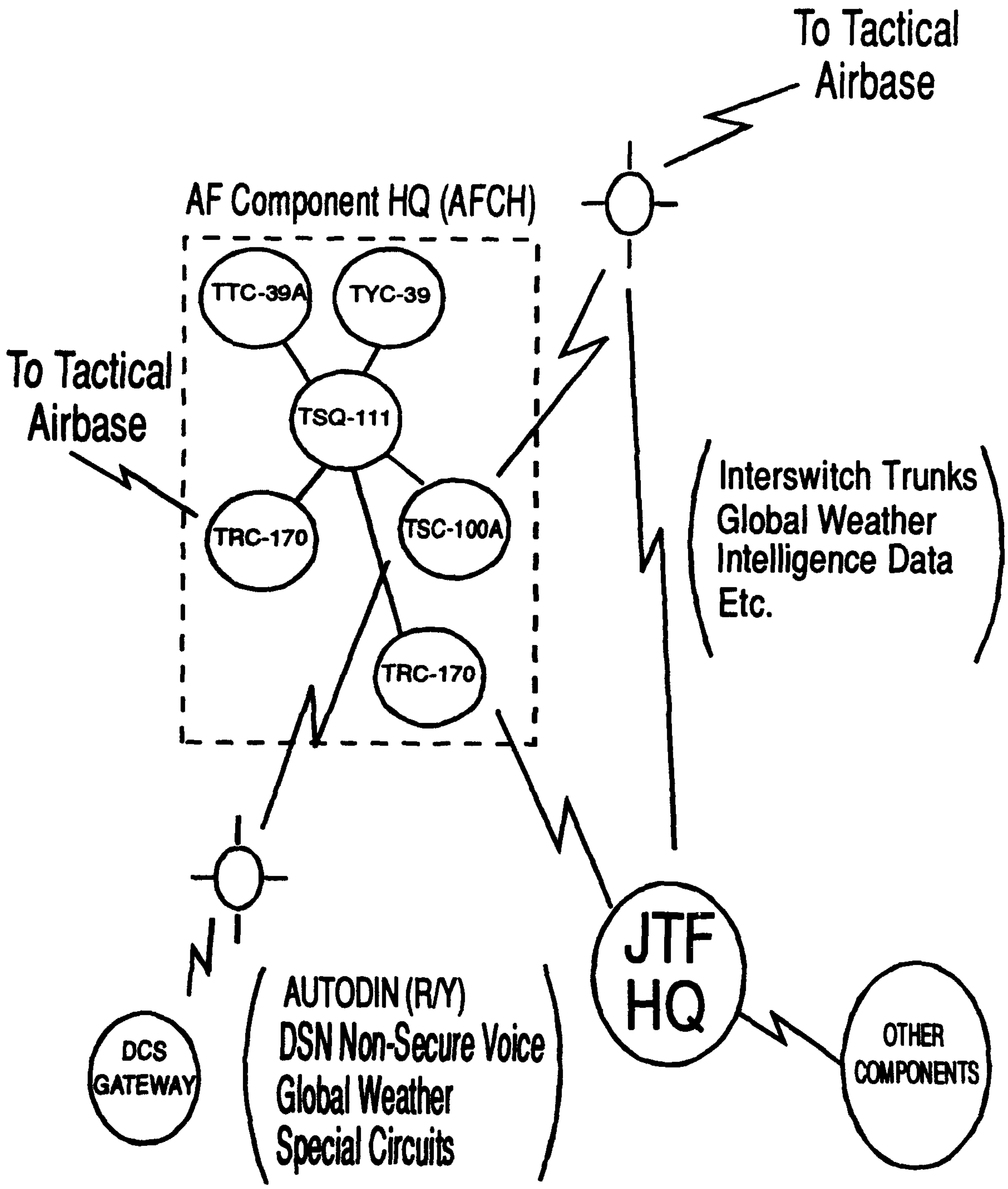

Figure 1. Air Force Component Headquarters Network

Note that the AFCH is also linked into the strategic network by way of a DCS satellite gateway. Depending on the particular scenario, the gateway could either be in CONUS, Europe, or Pacific. These TRI-TAC-to-DCS gateways are critical because they facilitate links between rear support bases, headquarters, and forward deployed forces.

Within the AFCH, various key TRI-TAC components, such as the TTC-39A, TYC-39, and TRC-170, are interconnected through the TSQ-111 CNCE as described earlier. Links from the component headquarters to lower echelon tactical air bases are established using both terrestrial (tropo) and space (satellite) means as shown in Figure 1.

2. Tactical Air Base

Figure 2, on the next page, is an example of TRI-TAC employed in a tactical air base configuration. Note, both satellite and tropo links are providing connectivity to the AFCH [Ref. 44]. In this example, a sample breakout of customer telephones (KY-68 and TA-954) and transportable teletype (TTY) terminals is shown. Also, the diagram illustrates the usefulness of the RT-1462 TSSR in extending service to remote locations. Additionally, a remote multiplexer combiner (RMC) is seen providing further circuit extension on the remote end of the TSSR link. Figure 2 demonstrates one of the most flexible configurations available in the current TRI-TAC inventory.

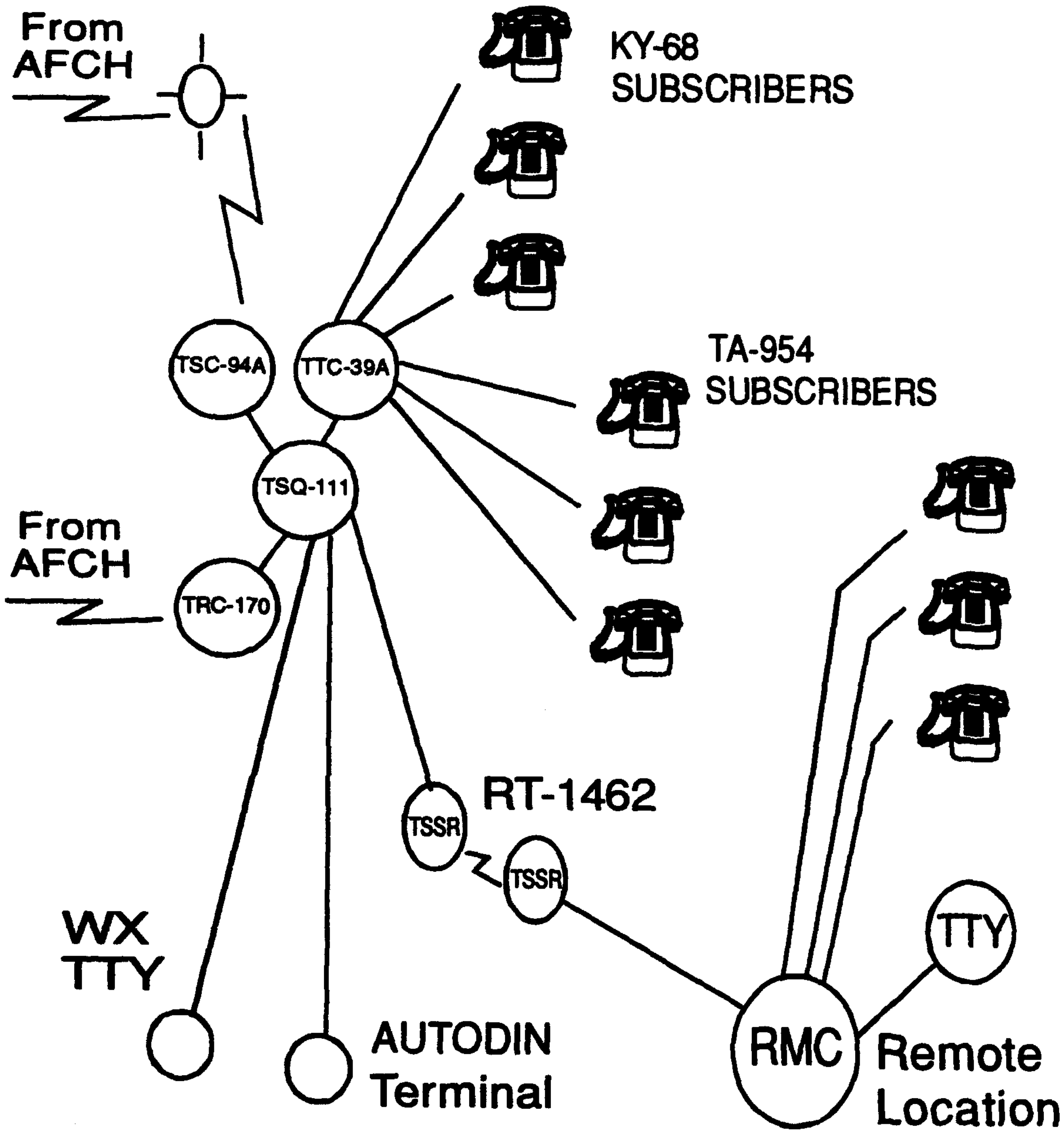

Figure 2. Tactical Air Base Network

3. Joint Message Switching

Figure 3 below depicts a typical joint message switching network [Ref. 44].

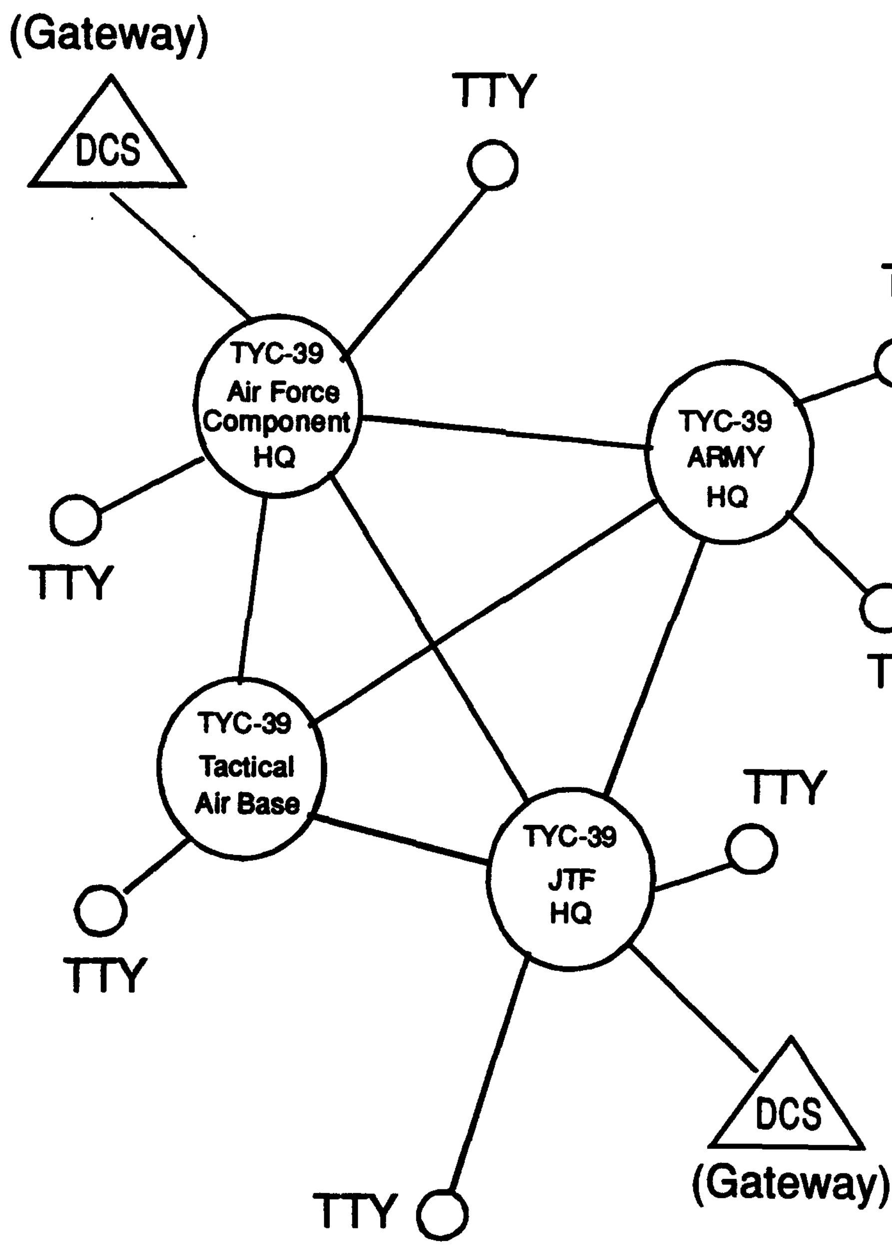

Figure 3. Joint Message Switching Network

Here, the importance of network survivability and redundancy is evident with the criss-crossing interswitch trunks (ISTs) in a mesh configuration. The 16 kbps ISTs, linking the TYC-39 Message Switches, are carried over various transmission media, including tropo, satellite, and cable. Numerous TTY terminals are also shown as direct connections off the TYC-39s. The DCS satellite gateways provide essential circuits between the TYC-39s and AUTODIN Switching Centers (ASCs). In some cases, high-frequency (HF) multi-channel radio links into DCS HF gateways are established as backups to the primary satellite links; however, HF AUTODIN entries afford a much lower data rate (75-300 baud vice 1200-2400 baud). Figure 3 depicts just one of many possible joint message switching network topologies.

D. SUMMARY

From its inception back in 1971, the TRI-TAC program has evolved to satisfy the need for interoperable and reliable communications at the Joint Task Force level. In practice, TRI-TAC has served the military services, and, in particular, the Air Force well. However, changes in technology and operational requirements have created some areas where TRI-TAC falls short. Operation Desert Shield/Desert Storm highlighted many of these problems which have acted as a stimulus for many proposed improvements. Chapter IV will identify the most significant recommendations for new Air Force tactical communications initiatives. These initiatives, coupled with

TRI-TAC's interoperability strengths and the amount of resources already invested, can provide the military services with a solid core of tactical communications well into the foreseeable future.

III. DESERT SHIELD/DESERT STORM COMMUNICATIONS

A. BACKGROUND

From TRI-TAC's beginnings in the Air Force Battlefield Environment (AFBE) in the early 1980s to recent operations in the Persian Gulf, numerous limitations have surfaced. Changes in technology and operational requirements have presented areas where the aging TRI-TAC equipment is deficient. More specifically, the lack of high-speed data and computer network support, and inadequate commercial interface capabilities have caused the greatest impact on recent military operations. This chapter describes TRI-TAC's employment and some of its more significant downfalls observed during Desert Shield/Desert Storm (DS/DS).

B. EMPLOYMENT OF TRI-TAC DURING DS/DS

1. Scope of Communications

Desert Shield/Desert Storm proved beyond a doubt that C4I is as fundamental to the fight as bombs, bullets, and airplanes. When properly employed, C4I becomes a vital force multiplier [Ref. 30: p. 4]. The forms of communications provided were voice, data, facsimile, record (message) communications, imagery, video, and e-mail. Mission/support areas covered included: Joint Forces Air Component Commander (JFACC), counter air, close air support (CAS), interdiction, suppression of enemy air defense (SEAD), refueling, airlift, search and rescue (SAR), special operations, and intelligence.

Additional mission areas included infrared electronic warfare (EWIR), air traffic control, aeromedical evacuation, supply, logistics, munitions, transportation, training, security police, and Office of Special Investigations (OSI). Other supported functions were finance, legal, medical, postal, combat control teams, combat camera, information management, audio visual services, public affairs, civil engineers, Moral Welfare and Recreation (MWR) services, chaplain, contracting, weather, and other airbase support operations [Ref. 24: p. 7]. Clearly, providing the required communications for employment of forces into a bare base environment can be quite a complex task. Communications requirements for all Air Force MAJCOMs and FOAs are consolidated and maintained by the Communications Requirements Data Base (CRDB).

The scope and pace of escalation of DS/DS was unprecedented. In fact, the operations in the Persian Gulf have been called "the largest single communications mobilization in military history." [Ref. 18: p. 25]. The scope of USAF activities alone are included in Table 4-1 on the following page [Ref. 18: p. 24]. It took more than 200 C-141 sorties to airlift tactical communications equipment to the Gulf [Ref. 18: p. 25]. During the early stages, these aircraft were not readily available for moving the bulky tactical and transmission equipment since the initial airlift was allocated towards the buildup of combat forces in theater.

While Air Staff planners estimated sufficient tactical

communications resources for 13 airbases, in the end, the Area of Responsibility (AOR) included 25 airbases. Compounding this serious shortfall, the Air National Guard (ANG), which had not been called to active service, possessed nearly 80 percent of Air Force tactical communications resources. As it turned out, the ANG provided only two squadrons and only about 10 percent of the overall resources [Ref. 18: pp. 25-26]. As a result, a sparse network of tactical communications were stretched to the limits in providing essential connectivity for theater-wide communications.

TABLE 4-1. SCOPE OF USAF ACTIVITIES

Quantity	Description
12	Combat Communications Squadrons
2300+	USAF personnel
1500	short tons of equipment
7000+	radio frequencies
26	SHF earth terminals
3	commercial T-1 satellite terminals
1050	USAF circuits
1000	miles of terrestrial systems
29	tropo and microwave links
6	DCS entry points
72	AUTOVON trunks
19	automatic telephone switches
17	manual switches
3	message switches
132,012	messages transmitted
1,293,775	messages received
59	communications centers
29,542,121	calls
350,000	air operations for Desert Shield
225,000	air operations for Desert Storm
950+	pages per Air Tasking Order

2. Switching and Transmission Networks

The TRI-TAC switching and transmission equipment formed a terrestrial system which interconnected the Joint

Task Force Headquarters, its component air, land, and sea commands and all locations within the AOR. The final system configuration stretched over 1000 miles and was comprised of 29 links of tropospheric and microwave transmissions [Ref 18: p. 30].

a. *Voice Network*

The voice network contained over 300 trunks connecting 25 TTC-39s in the theater to 8 DSN gateways (4 U.S., 3 Europe, 1 Pacific) [Ref. 18: p. 13]. Furthermore, it contained 19 automatic and 17 manual switchboards that processed nearly 30 million calls through 72 AUTOVON trunks [Ref. 18: p. 31].

b. *Message Network*

The message network contained 26 trunks connecting 20 TYC-39s in the theater to 5 AUTODIN switching centers (3 U.S., 1 Europe, 1 Pacific). Ultimately, 286 message centers were supported worldwide with an average delivery time of 23 minutes [Ref. 18: p. 15].

c. *Data Network*

Whereas TRI-TAC evolved to satisfy most of the voice and message traffic needs, little capability existed to cope with the data communications bottlenecks involved with large-volume, high-speed traffic of 1s and 0s. All four DDN networks were heavily used: MILNET was used for unclassified common-user service; DSNET1 was used for Secret level common-user traffic; DSNET2 was used for Top Secret and WWMCCS users;

DSNET3 was used for Top Secret/SCI intelligence support.

d. *Satellite Network*

The flexibility of space communications was demonstrated through extensive satellite usage in an effort to meet increasing traffic demands throughout the Gulf War. Initially, SHF Defense Satellite Communications System (DSCS) presence in the region consisted of only two satellites (DSCS East Atlantic and DSCS Indian Ocean) which handled a total DOD traffic throughput of about 4.5 Mbps (70 voice circuits equivalent) [Ref. 18: p. 122]. As hostilities heightened, so to did the need for greater communications throughput.

As U.S. forces in the Gulf peaked, a total of 4 DSCS satellites (East Atlantic, Indian Ocean, Indian Ocean Reserve, West Pacific Reserve) covered the region. The throughput climbed to 68 Mbps (1,100 voice circuits equivalent), and 110 earth terminals were deployed. Additionally, 9 UHF satellites from FltSatcom/AFSatcom and LeaseSat/Syncom, 2 experimental multiple access communications satellites (MACSAT), 2 United Kingdom Skynet satellites, 1 NATO, 4 IntelSat, and 1 InmarSat satellites were all deployed in support of coalition forces during DS/DS operations [Ref. 18: p. 123]. The Gulf conflict may be labeled as the first space war, and as a British defense chief simply observed, "The Gulf taught us that space has changed the whole nature of warfare." [Ref. 18: p. 133]

C. LIMITATIONS

Changes in technology and operational requirements have created areas where the existing TRI-TAC system falls short.

> Operation Desert Storm demonstrated that tactical communications are still plagued by incompatibilities and technical limitations. At CENTCOM corps and wing levels, a significant portion of the war was conducted over commercial telephone lines because of the volume and compatibility limitations of the military communications system [Ref. 42: p. 22].

This section does not discuss all the limitations of TRI-TAC, rather it focuses on some of the key shortfalls observed primarily from DS/DS operations.

1. General Observations from DS/DS

Desert Shield/Desert Storm (DS/DS) observations of deployed C4 systems [Ref. 31]:

- Inflexible equipment design
  - -- Current deployed systems are large and heavy
  - -- Automated deployed system hardware/software could not expand
  - -- CONUS automated systems are not structured to support deployed forces
- Inadequate communications capacity
  - -- Unique standards and inefficient communications limited throughput
  - -- Large capacity networks needed for sustaining operations
- Limited interoperability
  - -- Joint ATO planning/dissemination hampered by non-standard automated systems
  - -- Airborne communications and ground networks are not fully integrated.

2. Specific Problems from DS/DS

While not all of the communications problems from DS/DS can be identified here, this section hopes to highlight some of the more critical ones noted in Alan D. Campen's book, The First Information War [Ref. 18].

a. *Voice Network Problems*

Limited interswitch trunking resulted in poor voice switched network performance, with an average intra-theater grade of service ranging from only 40% to 85% call completion success rates [Ref. 18: p. 13]. The Ninth Air Force chief network systems engineer summed up the problems as a "disaster for call completion rates...we had a grid-locked, voice switched network." At one point, completion rates were reported as low as 5 percent for Routine, 40 percent for Priority, and 65 percent for Immediate [Ref. 18: p 32]. The unexpected use of modem-connected personal computers and facsimile machines over the circuit switched networks further compounded problems. The heavier traffic demands, coupled with many analog-to-digital conversions, and an abundance of protocol problems, all proved too taxing for a system which was not engineered to accommodate such applications [Ref. 18: pp. 13-14].

b. *Data Network Problems*

The lack of a pre-planned common-user data network for tactical communications via personal computers led to a number of problems. Poor circuit and end-to-end performance were the result of noisy, high error rate tactical circuits operating over non-commercial standard 16 kbps links. Also, due to traffic overload and corrupt address routing tables at DDN gateways, many Tranmission Control Protocol (TCP) timeout errors often occurred. Finally, the complex

configuration of routers, bridges, packet switches and satellite circuits were a network management nightmare [Ref. 18: p. 16]. As one Air Staff planner put it, "We had no plan for data communications." [Ref. 18: p. 32]

The lack of tactical communications networks that could provide the required in-theater data communications connectivity proved to be a major headache. Tactical planners greatly underestimated the sheer volume and variety of data required to support automated combat support systems. The new battlefield environment included literally thousands of personal computers. In the end, it is estimated that over 3000 computers were linked back to hosts in the U.S., mainly over leased commercial circuits [Ref. 18: pp. 32-33]. From the intelligence community's perspective, the tactical networks did not come close to meeting the data-intensive demands for supplying high-quality imagery down to the appropriate combat echelons. As a result, many units were limited to only hard copy photos delivered by helicopter or truck, often with unsatisfactory time delays [Ref. 18: p. 55]. In the author's assessment, the existing tactical systems could not possibly meet the excessive data communications requirements then, and most certainly, TRI-TAC will not be able to fully handle the new-age battlefield automation needs of the future.

D. SUMMARY

The existing theater deployable communications, TRI-TAC, are not geared for modern day warfare. TRI-TAC is primarily suited for simple voice and message traffic, but clearly, the widespread proliferation of personal computers, local area networks, high resolution imagery, and other high-speed data communications services have prompted the need for change. Operations during DS/DS demonstrated critical problems in supporting high-speed data communications, computer networks, and commercial interfaces as previously discussed.

> A potentially disruptive disconnect in planning allowed combat forces to arrive in the Persian Gulf without the communications equipment needed to plan, launch, and control air operations. And when the resources did arrive, they provided only marginal support for critical data communications, the service needed most in modern air warfare [Ref. 18: p. 35].

The TRI-TAC program has served its purpose for interoperable and reliable communications over the past couple decades, but advancements in technology and increased operational requirements call for theater deployable communications to keep up with the pace.

IV. THEATER DEPLOYABLE COMMUNICATIONS FOR THE FUTURE

A. LESSONS LEARNED

Lessons learned from DS/DS show that reliable, long-range mobile communications are essential on the modern battlefield. Theater Deployable Communications (TDC) must be capable of supporting a full range of communications and providing timely and accurate situational awareness for effective command and control during highly fluid conflicts.

> DS/DS demonstrated the inadequacy of current tactical communications systems and the value of a common picture of the battlefield to support effective Command and Control (C2) on-the-move (OTM). A persistent problem experienced was that the fighting forces moved faster than the communications infrastructure could effectively support. This, coupled with an incomplete common picture of friendly and enemy information, had a negative impact on the management of the battle [Ref. 27: p. A-15].

Building an up-to-date graphical common picture of the battlefield is a powerful tool for improving a tactical commander's situational awareness, and existing systems have proved inadequate in this respect. Today's generation of deployable communications equipment will not support tomorrow's missions of power projection on a global scale.

B. GLOBAL REACH, GLOBAL COMMUNICATIONS

The Air Force's Global Reach, Global Power concept calls for communications which are small and lightweight for mobility, modular and scalable for tailored force projection, and seamless for rapid response on a global scale [Ref. 40]. Combat Air Forces' (CAF) Mission Need Statement (MNS) 311-92

on Theater Deployable Communications asserts the following:

> The Air Force needs a lightweight, modular, integrated deployable communications system to support command, control, intelligence, logistics, and other mission support functions throughout multiple employment scenarios from initial deployment through sustaining operations [Ref. 43].

As the author's observation, the U.S. military must increase efficiency of current systems through improved transmission switching, bandwidth management, information compression, network management, and SATCOM usages. The new TDC concept must look to commercial-off-the shelf (COTS) equipment for multi-band satellite communications, network management, modular switching, and other deployable systems which are compatible with existing TRI-TAC, STU-III, and DDN systems [Ref. 32].

C. THE FUTURE OF THEATER DEPLOYABLE COMMUNICATIONS

1. Theater Deployable Communications Goal

A primary goal of the TDC program must be to transition from unique tactical to commercial-standards-based switching and transmission systems. The intent is to reduce life cycle costs, improve interoperability with strategic and theater communications systems, optimize use of the existing commercial communications infrastructure in theater, and to provide additional capabilities not supported by equipment currently in the inventory [Ref. 24: p. 20]. Furthermore, TDC packages must be transportable by airlift, sealift, rail, or truck. Size, weight, power requirements, and equipment set-up

times must be kept to an absolute minimum to support transportation, deployment, and operations in a deployed environment [Ref. 24: p. 54].

2. Theater Deployable Communications Characteristics

In response to the many observations, limitations, and suggested improvements to existing TRI-TAC systems, the future Theater Deployable Communications must possess the following characteristics [Ref. 31]:

- Transportable (small, lightweight)
- Flexible (modular, scalable)
- Interoperable (common standards/protocols)
- Efficient (dynamic bandwidth management)
- Evolutionary (TRI-TAC compatible)
- Robust (multiple routing)
- Responsive (network management/control)
- Secure.

3. Theater Deployable Communications Impacts

If actions are not taken to provide the essential TDC for the future, then the U.S. military will continue to suffer the following consequences, as experienced during DS/DS operations [Ref. 31]:

- Communications will remain unresponsive to global reach, global power requirements.
  - -- Too big, too heavy, too inflexible
  - -- Not available when the warfighter needs it
- Communications capacity will remain inadequate.

-- Slow ATO preparation and distribution

-- No real-time intelligence for BDA

- Deployed communications networks will remain unique.

-- Insufficient information for mission planning

-- Expensive integration costs

- Existing communications equipment will become expensive to support and modify because of technology obsolescence.

The bottom line is, unless improvements are made to existing systems, an integrated global information network will never be realized, and future U.S. military operations will be severely impacted.

D. AIR FORCE INITIATIVES

In the author's opinion, the U.S. Air Force's vision is focused in the right direction for improving communications in upcoming years. Communications Squadron 2000 initiatives require that "...deployable C4I systems must be modular, lightweight, and much less airlift-intensive than the current systems." [Ref. 38: p. 6] Further emphasizing the need for improved TDC systems, the Communications Squadron 2000 concept focuses on C4I support of expeditionary warfare by "equipping the deployable communications units with lightweight, modular, interoperable C4I systems" [Ref. 38: p. 8]. Looking to the 21st century, the Air Force's C4I must:

> Shape a future where communications and automation tools, systems and people combine to surround every Air Force decision maker and war fighter with a transparent infosphere providing, on demand, any information required for the execution of the task at hand - reliably, securely, in any required form, anywhere [Ref. 30: p. 2].

Tomorrow's forces must be able to adapt, respond, and fight over great distances, and the accompanying communications systems must be ready, mobile, and able to meet changing contingencies.

V. CELLULAR TECHNOLOGY

In meeting the needs of tomorrow's tactical communications, a move towards PCS technologies may well serve the military into the 21st century. Since PCS is heavily based on cellular technology concepts, a brief discussion of the most significant cellular principles will be presented in this chapter. Subjects to be discussed will include: call handoffs, roaming, frequency reuse, cell splitting, radio frequency (RF) propagation limitations, and channel access methods. After a technical foundation has been established, the next chapter will address several mobile systems which will employ many of the concepts presented here.

A. CELLULAR DESIGN PRINCIPLES

1. Background

Fundamentally, "cellular" is derived from the idea that the communication architecture, at its root level, is composed of individual cells which represent a specified coverage area. A cell is traditionally represented as a hexagon for convenience in depicting interlocking, non-overlapping area coverage. Each cell contains its own antennas, radio equipment, power plant, and data terminals that collectively form the interface between the switching center, called the mobile telephone switching office (MTSO), and the mobile units [Ref. 15: p. 8].

Two key principles of cellular communications system have to do with *call handoffs* and *roaming*. If a mobile subscriber approaches a cell's boundary, where transceiver signal strengths are near threshold levels, then an automatic prompt is sent to the MTSO requesting a call handoff. In response, the MTSO queries nearby cell sites for acceptable mobile unit signal strengths, and establishes a call handoff to a new cell site destination. The mobile set is automatically switched to the correct frequency and power levels to ensure uninterrupted service [Ref. 7: p. 32]. If a mobile unit is operating outside the confines of its Cellular Geographic Service Area (CGSA), then it is defined as roaming [Ref. 7: p. 33]. The switch networking standard, IS.41, handles the protocols for inter-system handoffs, or roaming. The IS.41 roaming procedures allow cellular services to be relayed to mobile subscribers regardless of the assigned CGSA [Ref. 7: p. 34]. Both call handoffs and roaming are valuable features handled by all cellular systems.

Typically, a mobile set consists of a control unit, a transceiver, and a simple omnidirectional antenna system. As a bit of trivia, the small personal handsets are referred to as "portables," whereas the automobile phone sets are referred to as "mobiles." Additionally, the mobiles use a simple whip roof/glass-mounted antenna, with up to 3 dB gain, and can transmit several watts of power, while the portables usually employ a short telescopic antenna, with 0 dB gain, and

transmit on the order of milliwatts [Ref. 15: p. 171].

In discussing a cellular system structure, it is important to consider the issues of capacity, coverage, and performance. In doing so, the topics of *frequency reuse* and *cell-splitting* will be covered.

2. Frequency Reuse

Establishing an efficient frequency reuse pattern is the key ingredient to the cellular architecture. Cells must be appropriately clustered to efficiently utilize the entire frequency spectrum allocated. The frequency reuse pattern determines the frequency reuse distance, D, as seen in the below equation [Ref. 15: p. 52]:

$$D = R \times (3 \times N)^{1/2}$$

In this equation, D is the distance which must exist between two cells of different clusters in order for the same frequency to be used in both, without cochannel interference. R is the radius of each cell, and N is the number of cells per cluster in the reuse pattern.

For example, with a seven-cell reuse pattern, N=7, and a cell site radius, R=10km, the required frequency reuse distance, D, is 45.83 km. In comparison, reducing the cell site radius to R=1 km results in a frequency reuse distance of 4.583 km.

In the latter case, R=1 km allows us to reuse our allocated frequencies more often within the total area of coverage. As a result, the potential subscriber capacity is

greatly increased. Also, note that lower power transmitters are needed as the cell sizes decrease; the smaller, low-power PCS handsets are based on this concept.

3. Cell Splitting

Cell splitting also plays a key role in increasing capacity and improving performance in heavily used cell areas. As the key to congestion management, the original cell is split into a number of smaller cells so that the assigned frequency channels can be used more often. After splitting, a greater number of channels are available, and thus, the service capacity is increased for that area by a factor, N, equal to the number of new cells created [Ref. 17: p. 42].

PCS typically deals with a cell site radius, $R \leq 1$ km, which is often referred to as a "microcell." The value of R is largely determined by the cell site's transmitter power. In the previous equation, D is directly proportional to R, so reductions in R (down to about one kilometer) can result in tremendous increases in spectrum efficiency. Additionally, as R is reduced, transmitter power can also be reduced, and lower frequency reuse distances can be achieved. These advantages of microcell, or even smaller picocell, coverage areas are significant benefits of future PCS concepts over the traditional cellular systems.

B. RF PROPAGATION LIMITATIONS

In this section, the effects of the following limiting factors on RF propagations are discussed:

1. Free Space Propagation Loss
2. Foliage Loss
3. Adjacent Channel Interference
4. Cochannel Interference
5. Multipath Propagation
6. Noise.

1. Free Space Propagation Loss (FSPL)

This RF propagation characteristic actually makes the concept of cellular communications practical. After all, if the signal strength did not diminish as a function of distance, then frequency reuse between separate cells would not be possible due to interference. However, within larger cells having a radius of nearly 10 miles, FSPL must be considered [Ref. 15: p. 102].

As examples of the FSPL impact on the standard Advanced Mobile Phone System (AMPS), the following attenuations are typical [Ref. 15: p. 102]:

- Free Space (ideal)	= 20 dB / 10 miles
- Flat, open Earth's surface	= 43.5 dB / 10 miles
- City (New York)	= 50 dB/ 10 miles.

2. Foliage Loss

Any foliage along the path between the mobile and cell site contributes to the attenuation of the RF signal. Much uncertainty is involved here, dependent on the sizes of trees, branches, leaves, trunks, density of vegetation, season of the year, and other related factors which can absorb RF

energy. For a cell of size R=10 miles, we approximate a foliage loss to 20 dB for analysis purposes [Ref. 15: p. 116].

3. Adjacent Channel Interference

This occurs when the energy between adjacent channels overlaps, resulting in destruction of the original signal. As a result, adjacent frequency channels can not be used within a given cell without proper filtering; note, extra filtering boosts the cost of the transceiver components.

4. Cochannel Interference

This may be the most important constraint on cellular frequency reuse. Cochannel interference occurs when different cell areas, using the same channel, are in sufficient range for unintentionally intercepting each other's transmissions. This is a primary factor of concern for maintaining an acceptable cellular reuse distance, D, as previously mentioned.

5. Multipath Propagation

This occurs when radio waves are reflected from obstacles, or even the atmosphere, and can cause three primary effects [Ref. 17: p. 213]:

a. *Delay Spread*

This results when a radio wave takes alternate paths, of varying distances, from transmitter to receiver due to reflections. Thus, by the time a single radio pulse is received, its width has been spread.

b. Rayleigh Fading

This is a condition where many rapid fades occur over time as a result of dramatic changes to the radio wave's phase and amplitude. While similarly caused by reflections as mentioned above, the signal also undergoes rapid, deep fades in strength which clearly degrade signal quality. In a mobile environment, the rate of fading is compounded even further due to variations in the relative motion of the radio waves to moving objects.

c. Doppler Shift

This describes the variations in frequency of the received signal resulting from a mobile set relative to the cell site. This shift can be significant enough to induce a noticeable distortion since the transmitted power spectrum is shifted off the nominal center frequency of the received signal.

6. Noise

Noise can be categorized as either external or internal, and can generally be described as any undesired signal in a communication circuit. Internal noise, such as thermal noise, arises from within the communications components themselves. External noise, such as electric motors, power lines, neon signs, and the like, pose the most serious concerns to cellular operations.

All of the above RF propagation factors must be considered when engineering a communications system with the

best signal-to-noise ratio (SNR) and overall performance charactistics possible.

C. CHANNEL ACCESS METHODS

Frequency allocations for PCS, around the 2 GHz range, are currently under review by the Federal Communications Commission [Ref. 5: p. 23]. With only 20 MHz (1910 - 1930 MHz) of the spectrum projected for unlicensed PCS usage, it is clear that multiple access schemes must be employed for the sharing of a single communication resource. This section focuses on multiple access techniques such as:

1. Frequency Division Multiple Access (FDMA)
2. Time Division Multiple Access (TDMA)
3. Code Division Multiple Access (CDMA).

1. Frequency Division Multiple Access

This access scheme is used by the original analog cellular system in the U.S. known as the Advanced Mobile Phone Service (AMPS). The allocated frequency spectrum consists of a total bandwidth of 20 MHz in the 850 MHz region; typically, a single channel bandwidth is 30 kHz with guard bands serving as buffer zones between adjacent channels [Ref. 14: p. 479].

With this scheme, a subscriber is assigned a dedicated frequency channel for the duration of the call. Upon call termination, the channel is once again available for reallocation to another subscriber. Note that each mobile unit must be frequency agile in order to be tuned to all available frequencies.

2. Time Division Multiple Access

In this scheme, frequency channels are separated into discrete time slots and assigned to different subscribers at fixed time intervals. While FDMA uses frequency guard bands, TDMA uses time guard slots to buffer between adjacent signal transmissions [Ref. 14: p. 484]. With systems such as the European Group Special Mobile (GSM) digital cellular standard, a fixed number of time slots are grouped into a frame, and then each frame corresponds to a separate frequency channel [Ref. 6: p. 35]. Notice that this technique is really a combination of TDMA and FDMA since all available frequencies and time slots are available to the subscriber.

TDMA offers several advantages over FDMA, which makes it the preferred choice for cellular applications [Ref. 7: pp. 73-74]: several subscribers can transmit over a single frequency channel, thus permitting a more efficient use of the RF spectrum; since continuous transmission is not necessary, transmitter power can be better utilized, and duplexers are not required; ease of reconfiguration, through software upgrades, allows acceptance of changing bit-rate algorithms; and TDMA provides better resistance to cochannel and adjacent channel interference.

As a result of the above advantages, TDMA can provide greater system capacity through greater freedom of channel assignments among the cells in a given area.

3. Code Division Multiple Access

Employed by spread spectrum communication systems, which have been used exclusively by the military for decades, the CDMA method has only recently been adopted for public cellular system usages.

Spread spectrum methods mainly include *frequency hopping* or *direct sequence* techniques. In both techniques the signal power is spread out over the entire assigned bandwidth rather than concentrated into a specific band. Additionally, extremely low signal-to-noise ratios can be tolerated as result of very high processing gains.

a. *Frequency-hopping CDMA*

Frequency-hopping CDMA (FH-CDMA) assigns a short-term frequency slot to a user for data transmission, then after a brief interval of time, another frequency is assigned for the next time interval, and so on, until the entire message is sent. The frequency hopping pattern for each user is generated by a pseudo-random code. The processing gain for FH-CDMA corresponds to the ratio of the total frequency spectrum bandwidth to the frequency bandwidth for each hop [Ref. 11]:

$$G_{FH} = W_{ss}/ R$$

where W_{ss} is the system bandwidth and R is the data rate. If a FH system has a bandwidth of 850 Mhz and transmits data at a rate of 1.2 kbits/sec, then we get the following processing gain:

G_{FH} = 850 Mhz/1200 bps = 708,333 ==> 10 $\log_{10}$(708,333)

G_{FH} = 58.5 dB

Clearly, as we divide the allocated spectrum into more segments, with smaller bandwidths for each hop, then we can achieve tremendous processing gains.

b. *Direct-sequence CDMA*

Direct-sequence CDMA (DS-CDMA) combines the user's signal with another signal from a random-sequence generator in order to produce a (pseudo)random, high-rate bit stream covering the entire assigned spectrum. At the receiver, a correlator separates the random sequence from the original signal for further processing. Once again, the processing gain can be computed by the ratio of the channel bit rate, "chip rate" = R_p, to the transmitted data bit rate, R [Ref. 11]:

$$G_{DS} = R_p / R$$

If each terminal transmits at 1 kbps with a chip rate of 100 kbps, then we get the following processing gain:

G_{DS} = 100 kbps/ 1 kbps = 100 ==> 10 log10(100)

G_{DS} = 20 dB

c. *CDMA Advantages*

The advantages of CDMA, over FDMA or TDMA, for cellular uses include [Ref 10]:

- large subscriber capacity
- inherent high level of information security
- ease of conversion from analog to digital systems

- resistance to fading since the signal is spread/"hopped" throughout the entire frequency bandwidth.
- much lower power transmitters required due to high processing gains.

D. SUMMARY

As previously described, cell splitting, frequency reuse, and new CDMA techniques are the primary tools for capacity and performance enhancements over the current systems. PCS advancements in further cell size reductions, more efficient frequency reuse capabilities, and improved channel allocation will extend cellular communications to even more sophisticated capabilities for the future.

The ultimate technological vision of individuals carrying small, inexpensive, handheld communicators and being reached by voice or data with a single phone number at any time or place is the foundation for Personal Communications Services [Ref. 5]. Looking to the future, many Mobile Satellite Services (MSS) are being proposed for delivery of PCS worldwide by the turn of the century. The next chapter will provide greater insight to five candidate MSS systems for the future.

VI. COMMERCIAL MOBILE SATELLITE SERVICES

A. OVERVIEW

Mobile Satellite Services (MSS), which fall under the umbrella of Personal Communications Services (PCS), provide the greatest potential to improving tactical communications support of future military operations. Many planned commercial MSS networks could feasibly augment the current Theater Deployable Communications (TDC) in satisfying the military's needs for reliable and interoperable voice, message, and data communications worldwide. This chapter provides an overview of the following candidate MSS systems: GLOBALSTAR, INMARSAT, IRIDIUM, ODYSSEY, and ORBCOMM. While an exhaustive list of all available satellite systems is not presented here, the selected candidate systems do represent a valuable sampling based on their unique capabilities, advanced designs, and worldwide coverages.

B. CANDIDATE MSS SYSTEMS

The candidate commercial systems considered for inclusion in DOD's C4I architecture fall into one of the following three primary orbits for communications satellites [Ref. 33: p. 822]:

1. Low Earth Orbit (LEO)
2. Medium Earth Orbit (MEO)
3. Geostationary Earth Orbit (GEO).

The specific altitudes corresponding to these orbits will be described in subsequent sections.

The five systems selected for further consideration represent five different categories of MSS systems [Ref. 33: p. 822]:

1. LEO (bent pipe): GLOBALSTAR
2. LEO (crosslink): IRIDIUM
3. Little LEO (bent pipe): ORBCOMM
4. MEO (bent pipe): ODYSSEY
5. GEO (bent pipe): INMARSAT.

For future reference, *bent pipe* and *crosslink* are analogous to the respective manners in which satellite communications transmissions are relayed between two earth stations, or mobile units. With *bent pipe*, when pumping communications from earth station A, through a satellite "pipe," to earth station B, the information is "bent" at a single satellite and forwarded to the desired destination. Clearly, the communications satellite must be in clear view of both earth stations simultaneously for a successful link to be established. A *crosslink* system, such as IRIDIUM, operates in a similar manner, but may employ more than one satellite for relaying/hopping communications around the world. In this case, it is not a prerequisite for a single satellite to be in clear view of both earth stations for a successful link to be established. The terms *bent pipe* and *crosslink* have been adopted to describe the concepts of operations discussed

above.

The following sections provide a more detailed description of the candidate MSS systems.

1. GLOBALSTAR

a. Basic Description

GLOBALSTAR, proposed by Loral QUALCOMM Satellite Services, Incorporated, projects an Initial Operational Capability (IOC) in the year 1997 [Ref. 19: p. 5-71]. GLOBALSTAR's constellation will consist of 48 LEO satellites, using a bent pipe concept of operations, for providing full global coverage [Ref. 19: p. 5-54].

b. Technical Characteristics

For added insight, and a basis for comparison, some technical characteristics are worthy of particular attention here. The 48 circular orbiting satellites will maintain altitudes of 1389 kilometers, six satellites in each of eight 52 degree-inclined planes, with an orbital period of two hours [Ref. 19: p. 5-70]. GLOBALSTAR's hybrid multiple access technique employs time domain duplexing - frequency division - code division multiple access (TDD-FD-CDMA) and beam hopping techniques. Mobile satellite subscribers will transmit and receive frequencies in the L-band (1610.0 - 1626.5 MHz) through the use of an elaborate frequency reuse scheme which is transparent to the user [Ref. 19: p. 5-55]. The extent of technical detail will be similarly provided for other MSS systems under comparison.

c. Primary Services

Three primary services offered will be: radio determination satellite service (RDSS), providing position location tracking and messaging; voice and data services with connectivity to the Public Switched Telecommunications Network (PSTN); and voice and data services through connections with various private networks. Additional communications features will also be available such as facsimile, freeze-frame video, automatic answering service, and worldwide voice mail [Ref. 19: p. 5-54]. This fully digital system will provide over 134,400 full duplex voice channels with bit rates ranging from 2.4 kbps to 9.6 kbps [Ref. 19: p. 5-58]. Clearly, GLOBALSTAR can deliver a large range of services on a global scale and requires serious consideration for future military uses.

2. IRIDIUM

a. Basic Description

IRIDIUM's worldwide cellular personal communications service, proposed by Motorola, is projected for IOC in 1997 [Ref. 19: p. 5-94]. The IRIDIUM constellation will consist of 66 LEO satellites (versus 77 originally), using a crosslink concept of operations, for providing full global coverage [Ref. 22: p. 2].

b. Technical Characteristics

Some technical characteristics of interest are presented here. IRIDIUM's 66 satellites will orbit at an altitude of approximately 780 kilometers, with 11 satellites

in each of six 86 degree-inclined planes [Ref 22: p. 2]. Each satellite is networked, via communications crosslinks, to other satellites in either the same plane or adjacent co-rotating planes. The crosslinks work in the Ka-band at frequencies between 22.55 GHz and 23.55 GHz [Ref. 21: p. 2]. This valuable crosslink capability provides worldwide traffic routing and additional redundancy potential [Ref. 21: p. 63].

The IRIDIUM system heavily employs a cellular concept of operations for its satellite earth coverage. The satellites communicate with the pocket-sized, mobile IRIDIUM Subscriber Units (ISU) in the L-band (1616.0 - 1626.5 MHz) using a combination of a full-duplex Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) channel bursts of digital data [Ref. 21: p. 92]. Each satellite projects 48 L-band spot beams on the earth's surface to create a 48-cell pattern; the capacity of any given cell is 960 channels [Ref. 22: p. 3]. The 66 satellites can cover 3168 possible cells, with a 12-beam reuse pattern, which results in 180 channels for worldwide reuse [Ref. 23: pp. 3-4]. The influence of current terrestrial cellular networks is clearly evident in IRIDIUM's design.

c. Primary Services

The IRIDIUM system will offer a variety of global communications services to include: digital voice at 4.8 kbps; data at 2.4 kbps; and RDSS for automatic location, reporting, paging, and two-way messaging. Motorola projects

an estimated six million subscribers will benefit from IRIDIUM's services, once fully operational [Ref. 21: p. iv].

3. ORBCOMM

a. Basic Description

ORBCOMM, proposed by Orbital Communications Corporation, has an anticipated IOC around 1996 [Ref. 19: p. 23]. ORBCOMM's constellation will consist of 20 "Little" LEO satellites, using a bent pipe concept of operations, for providing worldwide services. ORBCOMM is classified as a "Little" LEO system, in comparison to other LEO systems such as GLOBALSTAR and IRIDIUM, due to smaller satellite size/mass, and lower frequency band allocations in the VHF/UHF range [Ref. 20: p. 2-3].

b. Technical Characteristics

Only those technical issues deemed pertinent to understanding the system's basic operations are addressed here. ORBCOMM's satellite constellation will be comprised of two configurations: a primary constellation of 18 satellites divided equally into three circular orbital planes, inclined at 40 - 60 degrees. A supplemental constellation of two satellites will orbit in orthogonal polar planes separated by 180 degrees. The combined constellations will orbit the Earth at an altitude of nearly 970 kilometers [Ref. 19: p. 4-20].

ORBCOMM subscriber equipment will operate in the VHF band at 137.2 - 138.0 MHz downlink frequencies and

148.0 - 148.85 MHz uplink frequencies. The system will employ digital packet switching for up to 21 uplink channels at 2.4 kbps and 19 channels at 4.8 kbps. Additionally, ORBCOMM plans to interface with the Global Positioning System (GPS) through implementation of a small UHF bandwidth allocation around 400 MHz [Ref. 19: p. 4-10].

c. Primary Services

ORBCOMM capabilities will mainly serve applications dealing with accidents, search and rescue, and emergency medical requirements for mobile subscribers. The system will not handle voice communications, rather it will only provide low-speed, alphanumeric transmissions. It is estimated that approximately 20 million U.S. subscribers, over 85 percent from emergency services, will benefit from the ORBCOMM system [Ref. 19: p. 4-11].

4. ODYSSEY

a. Basic Description

ODYSSEY, proposed by TRW, Incorporated, has an expected IOC by 1997 [Ref. 19: p. 5-113]. ODYSSEY is the only MEO system in consideration for MSS service in this study. ODYSSEY's constellation will consist of 12 MEO satellites, using a bent pipe concept of operations, for providing worldwide services [Ref. 19: p. 5-97].

b. Technical Characteristics

ODYSSEY's 12 MEO satellites will orbit in three circular orbital planes of four each, with a 55 degree angle

of inclination, an altitude of 10,354 kilometers, and an orbit period of six hours [Ref. 19: p. 5-107]. Each satellite will use 19 beams to employ a 19-cell system, with a 3-frequency reuse pattern yielding a frequency reuse factor of 6.33 [Ref. 19: p. 5-100]. The satellites can operate in multiple frequency bands to include L-band, S-band, and Ka-band. User/satellite uplinks operate at 1.610 - 1.6265 GHz (L-band) and downlink at 2.4835 - 2.500 GHz (S-band). Satellite/gateway uplinks operate at 29.8955 - 29.9963 GHz (Ka-band) and downlink at 20.0955 - 20.1963 GHz (Ka-band) [Ref. 19: p. 5-104].

The ODYSSEY Subscriber Units (OSU) will provide full-duplex communications by using a spread spectrum CDMA modulation technique similar to evolving cellular communications systems. These small hand-held devices, transmitting only 0.5 watts, can provide digital voice capability at 4.8 kbps, or data communications at 1.2 kbps [Ref. 19: p. 5-105].

TRW's MEO concept provides some advantages over LEO and GEO systems. In comparison to a LEO system, a smaller number of satellites are required for providing global coverage. In contrast to GEO systems, propagation delays are reduced, as are the required satellite antenna sizes for desirable cellular coverage patterns [Ref. 19: p. 5-97].

c. **Primary Services**

ODYSSEY will provide a wide range of mobile services including radio determination (RDSS), voice, data, and message communications. Initially, only North America will be serviced with dual coverage by two satellites. The initial capacity will be 4600 users, which translates to 2300 per satellite. However, upon full completion, additional ground stations will be in place for full global coverage [Ref. 19: p. 5-99].

5. **INMARSAT**

a. **Basic Description**

INMARSAT was established back in 1979 as an international consortium of countries dedicated to providing satellite communications for ships in distress [Ref. 19: p. 3-21]. Three generations of INMARSAT GEO satellites, using a bent pipe concept of operations, have evolved since initial operations began in February 1982. First generation INMARSAT satellites included leased systems such as Marisat, INTELSAT-V, and Marecs satellites. These satellites have been replaced by INMARSAT's own four satellites, known as INMARSAT-2. Four third generation INMARSAT-3 satellites, designed by GE Astro-Space, with communications payload by Matra Marconi Space, are scheduled for operation by 1995 [Ref. 19: p. 3-22].

b. **Technical Characteristics**

The proposed INMARSAT-3 constellation will primarily be discussed here. The four satellites will be

placed in geostationary orbits at any of the following degrees longitude: 15.5 W, 34 W, 55.5 W, 64.5 E, and 179.5 E [Ref. 19: 3-18].

The more robust INMARSAT-3 satellites will incorporate improvements over past INMARSAT generations. The use of spot beams will permit increased transmitter power to mobile terminals and an added frequency reuse capability [Ref. 19: p. 3-11]. INMARSAT-3 operates in both the L-band and C-band frequency ranges: uplink frequencies use 6.425 - 6.454 GHz (C-band) and 1.6265 - 1.6605 GHz (L-band); downlink frequencies use 3.600 - 3.629 GHz (C-band) and 1.525 - 1.559 GHz (L-band) [Ref. 19: p. 3-13]. Various INMARSAT subscriber terminals are available for different applications; however, in general, voice and data rates range from 2.4 kbps to 9.6 kbps [Ref. 19: p. 3-15]. The INMARSAT family of satellites should provide a variety of services well into the 21st century.

c. Primary Services

It is estimated that more than 232,000 mobile terminals will be in use by 1995 [Ref 19: p. 3-29]. The INMARSAT system provides many services such as: digital voice, data, facsimile, store-and-forward messaging, position reporting, and emergency alerting [Ref. 19: p. 3-1]. From its roots onboard ocean-bound vessels, INMARSAT has expanded its services to ground and air forces as well.

VII. FRAMEWORK FOR COMPARISON

A. PURPOSE

To help solve the communications problems identified in previous chapters, the benefits of new PCS technologies require further investigation. More specifically, the Mobile Satellite Services (MSS) such as GLOBALSTAR, INMARSAT, IRIDIUM, ODYSSEY, and ORBCOMM are considered as viable candidates for augmenting DOD's communications architecture and improving voice, message, and data communications during JTF operations. Though the past does not necessarily represent the nature of future conflicts, and communications systems must be able to accommodate a wide range of requirements, for the purpose of this study, the author suggests that the candidate systems be compared within a scenario similar to the Persian Gulf War.

B. SCOPE

The scope of this study will be kept to a manageable size. In doing so, only the five previously discussed MSS systems, and the below-specified MOPs, MOE, and MOFE will be used for evaluation and analysis purposes. Given an appropriate cross-section of available technologies, and a fair assessment of the critical comparison measures, this study will provide a meaningful framework for identifying potential tactical communications improvements for the future.

C. DESIGN

1. Assumptions

A simulation or wargaming tool is available which will serve as a valid model for providing accurate information flow and measuring the subsequent impacts of various C4I systems.

A baseline of communications traffic, which is accommodated by existing networks, will serve as a basic load during each simulation/wargame iteration.

In establishing equitable grounds for comparison, the expenses incurred for program management, research and development, procurement, satellite launches, and operational costs are regarded as sunk costs to the respective commercial vendors. The government will only be charged for services rendered, which may reflect the activity costs above. Since future service prices are not readily available at this time, a final assumption is made that the commercially-owned MSS systems will offer competitive services for comparable costs.

2. Factors

This study will use five factors, corresponding to the five MSS networks, and will evaluate each factor at various levels of utilization for voice, message, or data communications traffic. Additionally, any combination of the five systems can be simultaneously incorporated into the communications infrastructure, in varying capacities, to provide a wide range of communications capabilities.

Considering five candidate MSS systems, a total of 32 (2^5) alternative communications architectures is possible. A subset of these architectures is presented in next subsection.

For each factor combination, varying levels of utilizaton can be assigned for voice, message, or data communications traffic. For instance, if only one system is under evaluation, then 100 percent of the inputed voice, message, and data traffic requirements must be met by the single system. Notice that not every system may have the capability to singularly handle all of the required services; subsequently, a lower rating would be assigned in this area. However, 100 percent of the required services may be handled by a single system, but this may be at the expense of longer time delays. At this point, mixing the percentages of voice, message, and data traffic taskings over different systems may alleviate the burden on any one system. Undoubtedly, each MSS system has its strengths and weaknesses, and through appropriately combining these systems, the proper blend of services should achieve maximum overall system performance.

As an example, for a two-system combination, several possible utilization schemes exist: 50 percent of all traffic equally divided amongst the two systems; or 75/25 percent split of all traffic allocated between the two systems; or 100 percent of voice on one system, with 50/50 message allocation, and a 75/25 data communications split. Clearly, many combinations can be programmed into any given scenario. Keep

in mind, this example only illustrates a few of the possibilities with only a two-system combination; three-system, four-system, and five-system architectures inherently promote even greater complexity. For the purposes of this study, the author suggests that all types of services be optimally distributed, via simulation software, amongst the combined systems to achieve maximum overall utilization.

3. Setup

In order to fully realize the beneficial qualities of each of the candidate MSS systems, while still limiting the scope of the study to a manageable size, it is recommended that the following thirteen architectural alternatives be considered:

1. GLOBALSTAR
2. IRIDIUM
3. ORBCOMM
4. ODYSSEY
5. INMARSAT
6. GLOBALSTAR-ODYSSEY
7. GLOBALSTAR-INMARSAT
8. IRIDIUM-ODYSSEY
9. IRIDIUM-INMARSAT
10. GLOBALSTAR-ODYSSEY-INMARSAT
11. IRIDIUM-ODYSSEY-INMARSAT
12. IRIDIUM-ODYSSEY-INMARSAT-GLOBALSTAR
13. GLOBALSTAR-ODYSSEY-INMARSAT-IRIDIUM-ORBCOMM

The thirteen above-selected combinations provide a substantial cross-section of the different technologies proposed to be operational by the turn of the century. With items 1 - 5, it is important to examine each of these systems separately to serve as a control group for further comparisons. Combinations 6 - 9 couple a LEO system (GLOBALSTAR or IRIDIUM) with either a MEO system (ODYSSEY) or a GEO system (INMARSAT). Items 10 - 11 combine all three types of systems to include LEO (GLOBALSTAR or IRIDIUM), MEO (ODYSSEY), and GEO (INMARSAT) systems. Notice, combinations 6 - 11 collectively serve as a baseline for comparison between the interchanged LEO systems, GLOBALSTAR and IRIDIUM. Lastly, in order to observe the incremental value of incorporating all five candidate MSS systems, the final composite architecture is proposed. Once again, the simulation's traffic analysis software will determine the most advantageous path to route communications based on speed, capacity, and connectivity considerations.

4. Measures

The study will rate the five systems based on the specified Measures of Performance (MOP), one Measure of Effectiveness (MOE), and one Measure of Force Effectiveness (MOFE) listed below. An appropriate rating scale for each measure will be dependent on the particular measure under evaluation. Unless noted otherwise, the simulation/wargaming tool will provide all necessary information required to assess

each of the desired measures.

a. *Measures of Performance*

This study will evaluate each of the candidate systems based on the following MOPs:

- *Speed* measures how fast, in seconds, information is transferred from point A to point B. This is simply measured by a system's responsiveness and timeliness for delivering voice, message, or data traffic between two designated locations.

- *Capacity* measures "size of the pipe," in bits-per-second (bps), for tranferring information from point A to point B. This is measured by how much information throughput is permitted through a system over a specified period of time.

- *Connectivity* measures the percentage of total network nodes covered during specified JTF operations. This measure includes the coverage provided to nodes in the JTF's Area of Responsibility (AOR), as well as coverage to essential reach-back nodes worldwide. In addition to the simulation tool, the respective commercial MSS system descriptions will be helpful in rating connectivity.

- *Availability* measures the percentage of time that a system provides uninterrupted services. This is measured by how much uptime divided by total time (uptime + downtime) can be expected for any particular system. Each system's advertised availability percentages should be obtained from the respective vendors and incorporated into the simulation

software.

- *Flexibility* measures the number of services provided. This is measured by how many different types of services are available to mobile subscribers. Implicit in flexibility is one's ability to configure a system to function in different capacities. Once again, the respective system descriptions will be useful in assessing this measure. Also, the simulation results should reflect the various services provided by each system in a given scenario.

- *Transportability* measures the ease/timeliness of deployment based on physical dimensions and required transportation. This is measured by the number of C-141 equivalents required to deliver the necessary resources to desired locations within the theater of operations. Factors such as size, weight, and modularity are typical considerations for determining transportability. In turn, each of these factors contributes to the timeframe required to move the necessary equipment to the appropriate battlefield locations.

- *Interoperability* measures the weighted number of successes versus deficiencies in interfacing with existing systems. This is measured by how well a system works within the given communications infrastructure. For instance, a proposed system may work well with one component of the TRI-TAC system, but not very well with another component. However, different levels of importance may be associated with

one component versus another. As an example, the proposed system may operate effectively with a less significant remote multiplexer combiner (RMC), but it may not work at all with a major device such as the Communications Nodal Control Element (CNCE), TSQ-111. The critical deficiency is clearly the more prominent factor here. Notice that interoperability problems are often reflected in other MOPs such as speed, capacity, availability, and flexibility.

- *Security* measures the level of secure communications permitted with existing encryption interfaces. This is measured by the classification level of information which is allowed to be carried over a given system. Multi-Level Security (MLS) is a key element desired by future military systems for providing a broader range of communications capabilites. Basically, the issue of security is tied to a system's compatibility with existing encryption devices such as the STU-III or other accredited encryption algorithms. Higher classification levels clearly offer a greater degree of flexibility for military operations.

b. Measure of Effectiveness

The MOE will be the probability that the overall communications system will provide the right information to the right place at the right time. A good simulation tool becomes valuable here for keeping track of the complex flow of information throughout every facet of the communications system. The study should be designed such that

specified locations are required to receive certain information within a given timeframe, and the simulation will reflect a system's ability to achieve the MOE. Additionally, an enormous amount of statistical data can be gathered for analysis of means, variances, standard deviations, and confidence intervals related to evaluating the MOE.

c. Measure of Force Effectiveness

The overall MOFE will be the success rate of the JTF commander in the execution of a campaign in any given geographic region. A wargaming tool, with human intervention, is valuable here for obtaining a fairly realistic assessment of the MOFE. In addition to the statistical analyses accumulated from the simulation tool, a valid wargame can determine how the various MOPs and MOE are related to a commander's situation awareness, performance of Command and Control (C2) functions, and successful conduct of military operations for a given scenario. The MOFE is simply measured by the outcome of the wargame scenario, either victory or defeat.

In the author's opinion, each of the above-selected measures represents a key element of C2, and together, contribute to the commander's situation awareness of the battlefield. In turn, the importance of collecting, processing, and disseminating the required information to all C2 echelons in a timely manner is reflected by the JTF's ability to achieve the MOFE.

5. Method

In weighing the candidate systems against multiple measures, at numerous levels, and determining incremental effects on an overall Measure of Force Effectiveness (MOFE), many complexities may arise. Due to the sheer number of possible outcomes, *simulation* and *wargaming* are preferred methods for obtaining accurate and useful results. The demonstrated capabilities of present modeling and simulation tools are well-suited for such a study.

An appropriate simulation/wargaming tool must possess characteristics which are directly applicable to the evaluation of the comparison measures specified in the previous subsection, C.4. For simulating communications traffic flow in various forms (voice, message, and data), the tool must provide traffic flow analysis and routing over the different media routes throughout the system. Basically, as inputs, the simulator should accept varying amounts of communications required to be transmitted in various forms. Also, any combination of implementing the candidate systems should be allowed as a possible means of handling the communications inputs. Thus, not only could observations be made concerning the impact of increasing throughput demands on any one system, but the incremental effectiveness of adding any other system to the overall architecture could also be investigated. As outputs, the simulator should provide communications traffic results which accurately indicate the

routes, throughputs, and timeliness of relaying the required information between desired locations, as determined by a given scenario. This method of study should provide a solid statistical foundation for comparing the technical capabilities of each system under investigation.

In conjunction with the number-intensive simulation method described above, a wargaming model, with a "man-in-the-loop," can provide valuable insight to determining how varying degrees of available information can impact one's ability to make good decisions. Along with assessing the completeness, accuracy, and timeliness of information from different systems, a wargame also demonstrates the human interaction within a given environment. As a result, this method of study builds on the statistical foundation by comparing candidate system improvements to a commander's situational awareness, and ultimately, determining various impacts on meeting the MOFE.

D. OTHER CONSIDERATIONS

In choosing the "best" C4I infrastructure to support a JTF at the turn of the century, while realizing that newer technologies will continually make current systems obsolete, total life cycle costs must remain as a primary concern. In these austere budget times, the chosen system must achieve the goal of minimizing life cycle costs while still meeting the necessary performance constraints. A tradeoff analysis between operational costs and performances, though beyond the

scope of this thesis, should be performed as a final comparison between the proposed systems.

Additional system performance considerations are discussed here with a focus on their relation and interaction with the existing C4I system environment:

- *Top level system requirements:* The system must provide timely interaction and sufficient support (hardware, software, maintenance, and personnel) to all facets of the C4I infrastructure so that overall JTF requirements are met.

- Physical technological feasibility: New hardware/software must be readily available and provide form, fit, and function compatible with current resources.

- *Human information processing limitations:* Large-scale system operations and time-critical tasks must include proper automation tools for information/equipment tracking, routing, scheduling, and overall network management.

- *Environment/Location requirements:* Effectiveness and reliability must continue to meet C4I needs in the event of changing battle conditions such as weather, terrain, and political animosity. The system must be able to adapt to these variations in order to satisfy the C4I mission.

- *Current inventory of physical assets:* All existing system entities must be utilized, updated, replaced, or discarded in such a manner which is compliant with minimizing life cycle cost.

The above-mentioned system requirements, though beyond the scope of the study's initial design, should ultimately be considered as part of a more extensive cost effectiveness analysis.

VIII. CONCLUSIONS

Technological research and development will continue at a feverish pace, but production and procurement of high-tech gear will be limited to the absolute essentials for satisfying the U.S. National Military Strategy [Ref. 41: p. 25]. As the future brings increased uncertainty in regional "hotspots" worldwide, coupled with decreasing budgets and resources, the U.S. military will continually be tasked to do more with less. In these times, when military downsizing/restructuring continues to exacerbate shortfalls in manpower and aging systems, advanced technologies must be pursued if we are to keep the edge over our adversaries. Future military operations and emerging technologies require that periodic adjustments be made to existing systems to achieve needed improvements in performance, reliability, availability, maintainability, and mobility. The existing Tri-Service Tactical Communications (TRI-TAC) program has reached a crossroads in time, and a change in direction is necessary. The military's communications superhighway must expand its onramps to handle the increased traffic demands of regional conflicts on a global scale.

Personal Communications Services, particularly in the area of Mobile Satellite Services (MSS), provide new potential for meeting future mobile communications requirements. The five commercial systems (GLOBALSTAR, INMARSAT, IRIDIUM,

ODYSSEY, and ORBCOMM) described earlier are all viable candidates for augmenting the TRI-TAC system. Commercial-Off-The-Shelf (COTS) technology is available for providing transportable, flexible, interoperable, efficient, evolutionary, robust, and responsive battlefield communications. The previous chapter serves as a framework for comparison of five such COTS systems. Using simulation and wargaming tools, critical MOPs, MOEs, and MOFEs can be assessed against a wide range of communications requirements. Follow-up studies should be conducted, in accordance with the design presented in Chapter VII, to determine which communications architectures and systems are best suited for meeting the military's needs.

Clearly, PCS, if properly implemented, can greatly contribute to the improvement of Theater Deployable Communications for the future. PCS represents a large piece of the puzzle in C4I for the Warrior's quest for "a global network of military and commercial communications systems and networks linking information data bases and fusion centers that are accessible to the Warrior anywhere, anytime, in the performance of any mission." [Ref. 29: p. 10]

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